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RESEARCH

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Genotype-environment interaction and yield stability of five *Vigna radiata* genotypes under contrasting agrivoltaics environments in a tropical dry season climate

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Abstract

Background: The push for net-zero CO_2 emission in the energy sector by 2030 has led to massive investments in clean energy sources in several countries. One such investment is in photovoltaics which are substances that convert solar energy into electricity. Due to the large land requirement for the installation of photovoltaic plants, a significant portion of agricultural lands have been converted to photovoltaic facilities in recent times. Land use conflicts between food and energy production are becoming an increasing concern that needs addressing. Agrivoltaics presents an opportunity to integrate crops underneath photovoltaic panels sustainably. The objective of this study was to select genotypes with superior yield advantage and greater stability underneath the APV system. Methods: Five mungbean genotypes, Tvr18, Tvr28, Tvr65, Tvr79, and Tvr 83 were assessed under contrasting APV microenvironments, WPV, EPV and NPV at the National Center for Energy Research, University of Nigeria, Nsukka. The experiment was a split-plot design with APV as the whole-plot factor while genotype was the sub-plot factor with five replications. Results: The additive main effects and multiplicative interaction (AMMI) analysis showed significant genotype, environment, GxE, IPCA1, and IPCA2 effects ($p < 0.05$) for seed weight. Two genotypes, Tvr28 (9.92 g) and Tvr83 (9.58 g) recorded higher seed weights across environments. The EPV environment recorded higher seed weight per plant (10.51 g) than NPV (7.58 g) and WPV (5.44 g) environments, respectively. Tvr18 and Tvr65 were the most unstable genotypes across the APV-environments with higher IPCA1 (−1.75 and 1.30, respectively) and ASV (4.02 and 3.00, respectively) scores in contrast to Tvr83 and Tvr28 with the least IPCA1 (0.19 and 0.09) and ASV (1.23 and 1.18, respectively) scores. Hence, Tvr83 and Tvr28 were more stable across the APV microenvironments and were the best in seed yield.

Keywords: agrivoltaics, agrophotovoltaics, GGE analysis, genotype × environment interaction, AMMI, mungbean

Introduction

Food security is increasingly at risk as agricultural lands are being converted into more profitable photovoltaic (PV) power plants (Kienast *et al*., 2017; Farja and Maciejczak, 2021; Havrysh *et al*., 2022; Moscatelli *et al*., 2022). By 2030, the International Energy Agency (IEA) aims for net-zero CO_2 emissions in the energy sector by expanding solar and wind energy production (Farja and Maciejczak, 2021), which could further encroach on agricultural lands due to the large space required for PV installations. Therefore, improving land-use efficiency is essential if the goal to end hunger by 2030 is to be achieved (United Nations Climate Change Annual Report, 2020).

Agro-photovoltaics, or agrivoltaics (APV), is an innovative approach that allows for simultaneous crop cultivation and electricity generation by installing PV panels over farmland. This technology offers a promising way to balance future food and energy demands (Ravishankar *et al*., 2021) in order to increase land-use efficiency (Touil *et al*., 2021), reduce instantaneous solar radiation by 40% (Allardyce *et al*., 2017; Dijk *et al*., 2021), and enhance photosystem II (PSII) efficiency (Ravishankar *et al*., 2021; Ukwu *et al*., 2023a), which is positively linked to yield (Xu *et al*., 2020). Furthermore, electricity generated from PV can power farm equipment, and shading can help conserve water during dry spells, providing cost-saving benefits.

Mungbean (*Vigna radiata* L) is a valuable, short-season legume widely grown in tropical and subtropical regions for its protein-rich edible seeds. It is a dietary staple and income source for smallholder farmers in South and South-east Asia. Mungbean, a warm-weather

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crop, relies on ample sunlight for optimal photosynthesis, biomass accumulation, and yield. While some studies indicate that shading can negatively impact growth processes such as photosynthesis, respiration, and nutrient uptake, the degree and duration of shading are key factors influencing these effects.

Genotype by environment (G × E) interaction is an important component in multi-environment experiments due to its role in the expression of the phenotype, hence, it is very important for the evaluation, selection, and recommendation of crop varieties (Mattos *et al*., 2013; Regis *et al*., 2018). G × E interaction refers to the differential response of a genotype across different environments (Bavandpori *et al*., 2015). It is of great interest to plant breeders because a large interaction could reduce gains from selection, consequently reducing the success rate of identifying superior genotypes (Kamila *et al*., 2016). A substantial G × E interaction is seen in the fact that genotype performance in multi-environment trials frequently varies from one environment to another. Finding the environment that most closely resembles the ideal environment requires evaluating many genotypes in a multi-environment (Yan, 2001). The ideal genotype should, in particular, perform consistently and be widely adapted to a variety of environments. Hence, to determine the percentage of observable variation that is predictable and the component that is unpredictable, plant breeders are interested in measuring G × E interaction. The additive main effects and multiplicative interaction (AMMI), and the genotype main effects and G × E interaction effects (GGE) models (Yan and Kang, 2003) are two frequently used statistical models for G × E analysis (Gauch, 2006). Earlier researchers have focused on evaluating the growth and yield responses of mungbean to fertilizers (Ihejiofor *et al*., 2020, 2022), morphological variation among genotypes (Yoseph *et al*., 2022; Ukwu *et al*., 2023b), spacing requirements (Ukwu *et al*., 2023c), growth and photosynthesis responses underneath the APV (Ukwu *et al*., 2025). There is no evidence of genotype × environment, and stability assessment of crops grown under an APV system in literature as a prelude to a meaningful selection of an ideal genotype. This consideration formed the basis for conducting this present research. The objective of this study was to select genotypes with superior yield advantage and greater stability underneath the APV system. This is the first report on the assessment of genotype by environment interaction and yield stability under an APV facility.

Methods

EXPERIMENTAL MATERIALS, DESIGN AND SITE

Five mungbean genotypes, Tvr18, Tvr28, Tvr65, Tvr79, and Tvr83 were grown under three APV microenvironments [East-West facing PV (WPV), West-East facing PV (EPV) and no-PV)] in a split-plot design with five replications at the Center for Energy Research and Development, University of Nigeria, Nsukka, Enugu State, Nigeria (6°51'57"N 7°24'57"E) between December 2022 and March 2023. The three APV environments constituted the whole-plot treatment while the five genotypes of mungbean constituted the sub-plot treatment. Nsukka has mean annual rainfall of 1276 ± 706 mm, solar radiation of 1452 ± 269 w m^{-2}, and temperature of 32±5°C (Okoro *et al*., 2021). Relative humidity varies and is influenced by season (rainy and dry seasons). The upper limit (about 89%) is usually experienced during the peak rainy season (July–August) while the lower limit (39–41%) occurs during dry spells (December and January).

CROP ESTABLISHMENT

Seeds were sown in 10 liter pots prefilled with inert coconut fiber dust and placed at a spacing of 40 × 40 cm. Two seeds were sown per pot and later thinned down to one-seed at 1 week after planting (WAP). Universal orange fertilizer (N – 16%, P_2O_5 – 5%, K_2O – 25%, MgO – 3.4%, Fe – 0.10%, Mn – 0.04%, B – 0.01%, Cu – 0.01%, Mo – 0.001%, Zn – 0.01%) was applied at the rate of 2 g/l or 20 g per pot. Watering was done once daily according to the ET_{Crop} (3–5 mm).

MICROCLIMATE DESCRIPTION OF THE APV ENVIRONMENTS

The microclimate parameters of the three APV environments showed significant variation (Ukwu *et al*., 2025). Photosynthetic active radiation (PAR) and temperature were lower underneath the WPV and EPV environments in contrast to NPV (Fig. 1). However, relative humidity was higher underneath WPV and EPV environments than NPV. PAR ranged from 107.8 to 157.0, 132.1 to 200.0, and 158.6 to 298.0 μmol photons m^{-2} s^{-1} underneath WPV, EPV, and NPV environments, respectively (Fig. 1). Variability in microclimate temperature ranged from 25.4 to 27.4, 26.2 to 28.3, and 27.0 to 29.2°C underneath WPV, EPV, and NPV environments, respectively. Similarly, variation in relative humidity across the APV environments ranged from 29 to 72%, 28 to 71%, and 27 to 68% underneath WPV, EPV, and NPV, respectively (Fig. 1).

STATISTICAL ANALYSIS

Data were tested for significance using the analysis of variance procedure. Significant treatments were separated using the least significant difference (LSD) at $p < 0.05$. Furthermore, the AMMI analysis was applied to separate variation in the yield data set into components, accounting for both main treatment effects and genotype-by-environment (G × E) interactions (Duarte and Venkovsky, 1999). This approach combines traditional ANOVA (analysis of variance) and PCA (principal component analysis) into a single analysis framework that includes both additive and multiplicative effects (Gauch, 1992).

The AMMI analysis followed a two-step process. First, standard ANOVA was used to estimate the main effects of genotype and environment. Then, PCA was applied to the interaction residuals. The AMMI model equation is as follows:

$$Y_{ij} = \mu + G_i + E_j + \sum \lambda k \alpha ik \delta jk + R_{ij} + \varepsilon$$

where Y_{ij} is the value of the i_{th} genotype in the j_{th} environment; μ is the grand mean; G_i is the deviation of the i_{th} genotype from the grand mean; E_j is the deviation of the j_{th} environment from the grand mean; λk is the singular value for PC axis k; αik and δjk are

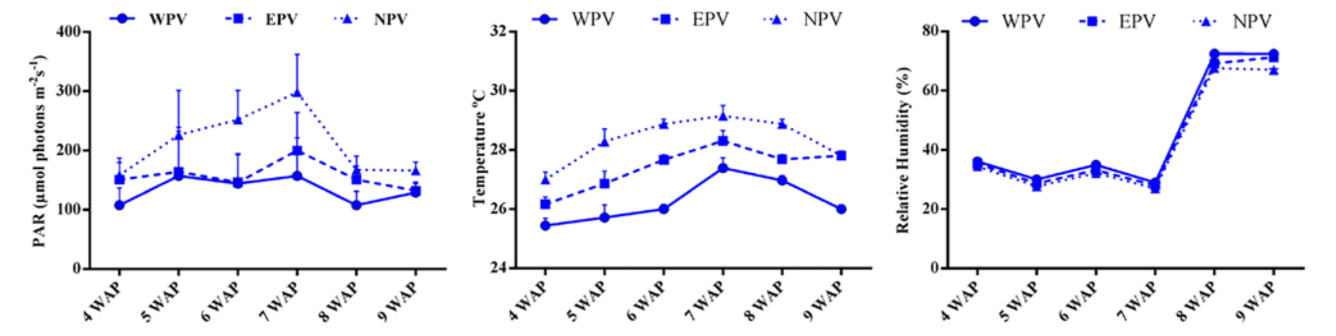

Fig. 1. Variability in microclimate variables underneath three APV environments used for the study. Data were taken between 9.00 am and 12.00 noon weekly. WAP: weeks after planting; WPV: East-West facing PV; EPV: West-East facing PV; NPV: no-PV.

the PC scores for axis k of the i_{th} genotype and j_{th} environment, respectively; R_{th} is the residual and ε is the error term (Gauch, 1992). AMMI's stability value (ASV) was calculated following the formula proposed by Purchase (1997) as follows:

$$ASV = \sqrt{\left[\left(\frac{SSIPCA1}{SSIPCA2}\right)(IPCA1SCORE)\right]^2 + (IPCASCORE2)^2}$$

where SSIPCA1/SSIPCA2 is the weight given to the IPCA1 value by dividing the IPCA1 SS by the IPCA2 SS; and the IPCA1 and IPCA2 scores are the genotypic scores in the AMMI model.

The GGE-biplot methodology, which is composed of two concepts, the biplot concept (Gabriel, 1971) and the GGE concept (Yan *et al*., 2000), was used to visually analyze the multi environment yield trial (MEYTs) data. This methodology uses a biplot to show the factors (G and GE) that are important in genotype evaluation and that are also sources of variation in G × E analysis of MEYTs data (Yan, 2001; Yan *et al*., 2000). The data was analyzed using Genstat statistical package, 18th edition.

Results

MAIN EFFECTS OF APV AND GENOTYPE ON YIELD COMPONENTS OF MUNGBEAN

Yield components of mungbean such as number of pods per plant (NOPP), number of seeds per plant (NOSPt), 1000-seed weight (1000 SW) and seed weight per plant were significantly affected by the APV system, whereas, pod length (PL), pod width (PW), number of seeds per pod (NOSPd) and average pod weight (PWt) did not show significant variation underneath the APV system (Table 1). NOPP, NOSPt and seed weight were significantly higher under the EPV whole-plot compared to the NPV and WPV plots. NOPP increased by 28% under EPV and decreased by 24% under WPV. Likewise, NOSPt and seed weight increased under the EPV by 25 and 38%, respectively but decreased under WPV by 31 and 28%, respectively.

Genotypic variation was observed in yield components of mungbean. Tvr28 genotype showed superiority in PL (7.52 cm), NOSPt (368.30), PWt (0.35 g), and seed weight (10.51 g). Tvr83 genotype was significantly higher in NOPP (49.50), Tvr65 recorded higher NOSPd (10.85) while Tvr18 had longer pods (0.56) and larger 1000 SW (64.33 g).

INTERACTION EFFECT OF APV AND GENOTYPE ON YIELD COMPONENTS OF MUNGBEAN

Yield components of mungbean were significantly affected by the interaction of APV environment and genotype (Table 2). The genotypes showed differential responses to the different APV environments. For instance, Tvr28 genotype showed superiority in NOSPt (463.40) and PWt (0.36 g). Tvr83 recorded the highest NOPP (61.20) and seed weight (9.92 g) in the NPV whole-plot compared to Tvr65 genotype under the WPV plot with the least NOPP (17.40) and seed yield (2.10 g). Tvr79 had a higher number of seeds per plant (531.00) under the NPV whole-plot compared to Tvr65 (165.20) under the WPV whole-plot which was the poorest. The highest pod length (7.93 cm) and number of seeds per pod (11.98) were recorded by Tvr79 underneath the WPV whole-plot compared to the least pod length (3.99 cm) and number of seeds per pod (6.06) recorded in Tvr83 underneath the NPV whole-plot. The highest 1000 SW was obtained by Tvr18 (31.40) under the WPV whole-plots while the genotype Tvr65 was the poorest (23.90 g) across the APV whole-plots.

AMMI ANALYSIS

The AMMI ANOVA results for mungbean yield are summarized in Table 3, showing the effects of genotype, environment, and genotype-environment (G × E) interactions, along with the sum of squares for the interaction principal component axes (IPCA). The analysis indicated that seed weight of mungbean was significantly affected by the environment ($p < 0.01$), genotype, and G × E interaction accounting for 48, 27, and 25% of the treatment variation, respectively. The environment accounted for the largest percentage of the total variation, an indication that at least one of the three APC environments was clearly distinct from the rest. This was further confirmed by the high sum of squares for the environment which significantly affected mungbean yield.

The yield scores of the interaction components, IPCA1 and IPCA2 for each genotype, along with the ASV are shown in Table 4. Three genotypes (Tvr79, Tvr83, and Tvr28) had low ASV scores (0.93, 1.18, and 1.24, respectively) indicating higher stability except that Tvr79 recorded below average seed weight and did not meet the ideal performance criteria. Consequently, Tvr83 and Tvr28, which had the next lower ASV scores after Tvr79 and recorded above-average yields, were considered more stable and superior.

Table 1. Main effects of PV-shading and genotype on yield components of mungbean.

Treatment	Number of pods/plant	Pod length (cm)	Pod width (cm)	Number of seeds/pod	Number of seeds/plant	Pod weight (g)	1000 seed weight (g)	Seed weight/ plant (g)
PV-shading								
WPV	24.40	6.51	0.50	8.98	205.30	0.31	27.79	5.44
EPV	41.40	6.71	0.55	9.33	370.90	0.32	31.55	10.51
NPV	32.20	6.75	0.50	9.49	296.30	0.29	26.95	7.58
$F\_LSD_{(0.05)}$	9.900	NS	NS	NS	62.090	NS	2.108	4.526
Genotype								
Tvr18	25.00	6.83	0.56	8.36	213.80	0.33	31.40	6.28
Tvr28	37.60	7.52	0.55	9.91	368.30	0.35	28.51	9.92
Tvr65	19.80	7.26	0.51	10.85	217.20	0.31	30.05	6.59
Tvr79	31.40	7.51	0.51	10.69	328.10	0.29	23.90	6.84
Tvr83	49.50	4.16	0.46	6.53	326.70	0.26	29.97	9.58
$F\_LSD_{(0.05)}$	7.630	0.373	0.022	0.774	63.560	0.041	1.125	2.035

WPV: East-West facing PV; EPV: West-East facing PV; NPV: no-PV; NS: means are not significantly different at $p < 0.05$.

Table 2. Interaction effect of PV-shading and genotype on yield components of mungbean.

PV shading	Genotype	Number of pods/plant	Pod length (cm)	Pod width (cm)	Number of seeds/pod	Number of seeds/plant	Pod weight (g)	1000 seed weight (g)	Seed weight/ plant (g)
WPV	Tvr18	22.80	6.25	0.53	7.39	171.60	0.35	35.50	5.92
	Tvr28	22.80	7.19	0.54	9.48	204.70	0.36	30.90	6.12
	Tvr65	17.40	7.00	0.51	9.48	165.20	0.27	17.00	2.10
	Tvr79	16.80	7.93	0.49	11.98	206.00	0.31	27.31	5.42
	Tvr83	42.30	4.18	0.43	6.60	278.80	0.25	28.26	7.60
EPV	Tvr18	22.80	6.91	0.59	7.94	181.40	0.34	33.14	5.83
	Tvr28	47.40	7.49	0.60	9.37	436.70	0.34	29.30	12.36
	Tvr65	22.80	7.56	0.51	12.38	282.70	0.36	41.08	11.33
	Tvr79	52.80	7.27	0.55	10.03	531.00	0.28	22.00	9.81
	Tvr83	61.20	4.30	0.49	6.93	422.50	0.28	32.24	13.20
NPV	Tvr18	29.40	7.33	0.55	9.76	288.40	0.31	25.55	7.08
	Tvr28	42.60	7.87	0.50	10.90	463.40	0.36	25.34	11.28
	Tvr65	19.20	7.22	0.51	10.69	203.80	0.30	32.06	6.33
	Tvr79	24.60	7.31	0.49	10.05	247.20	0.26	22.40	5.29
	Tvr83	45.00	3.99	0.46	6.06	278.70	0.23	29.42	7.92
$F\_LSD_{(0.05)}$		14.690	0.618	0.040	1.274	112.111	NS	2.038	5.217

WPV: PV facing west; EPV: PV facing east; NPV: No-PV shading; NS: means are not significantly different at $p < 0.05$.

Table 3. AMMI analysis of variance over three environments.

Source	Df	SS	MS	%Total SS	%Treatment
Treatments	14	679.0	48.5**	52.1	
Genotypes	4	185.0	46.3**		27.2
Environments	2	323.5	161.8*		47.6
Block	12	448.1	37.4**		
G × E Interaction	7	170.5	24.4*		25.1
IPCA 1	5	118.8	23.8*		69.7
IPCA 2	3	51.7	17.3		30.4
Residuals	<0.001	0.0	0.0		
Error	24	175.1	7.3	47.9	
Total	74	1302.3	17.6		

**Significant at 1% probability level.
*Significant at 5% probability level.

Table 4. Main effects of genotype and environment on seed weight, interaction principal components, and ASV of the five mungbean genotypes in three APV environments.

Genotype	WPV	NPV	EPV	Mean	IPCA1	IPCA2	ASV
Tvr18	5.92	7.08	5.83	6.28	−1.74	0.24	4.01
Tvr28	6.12	11.28	12.36	9.92	0.16	1.18	1.23
Tvr65	2.10	6.33	11.33	6.59	1.30	0.37	3.00
Tvr79	5.42	5.29	9.81	6.84	−0.05	−0.92	0.93
Tvr83	7.60	7.92	12.20	9.58	0.34	−0.88	1.18
Mean	5.44	7.58	10.51	7.84			
IPCA1	−1.32	−0.41	1.73				
IPCA2	−1.00	−1.43	−0.43				

Contrarily, Tvr18 (4.02) and Tvr65 (3.00) were unstable with lower yields, and hence, were poor APV performers.

The AMMI biplot showing the main effects on the x-axis and the IPCA1 values on the y-axis is presented in Fig. 2. Treatments that are positioned close to a vertical line exhibit statistically comparable main effects, while those near a horizontal line demonstrate comparable interaction patterns (Crossa *et al*., 1990). Research has shown that large IPCA1 scores whether positive or negative indicate strong interactions, whereas scores near zero signify weak interactions or stability.

The interaction principal components analysis in Table 2 revealed the level of interaction among the genotypes, and the APV environments. Two genotypes Tvr18 and Tvr65 had higher IPCA1 values (−1.76 and 1.30, respectively) and were the most interactive in contrast to Tvr79, Tvr28, and Tvr83 (−0.05, 0.16 and 0.34, respectively) which had lower values with minimal interaction. In addition, the NPV environment was the least interactive (−0.41) in contrast to the WPV and EPV environments with larger interaction coefficients (−1.32 and 1.73, respectively).

Genotype Tvr79 was situated close to the biplot origin in the IPC1 (Fig. 2) which further emphasized its stability across the APV micro-environments. However, it recorded very low seed yield which was below the grand mean. The trend was also similar for Tvr83 and Tvr28 which were situated close to the horizontal line with higher mean yields.

MEAN PERFORMANCE AND STABILITY OF MUNGBEAN GENOTYPES BY GGE BIPLOT

The which-won-where perspective, which offers a concise summary of the G × E interaction pattern of a multi-environment yield trial data set, is shown in Fig. 3. The vertex genotypes (Tvr18, Tvr28, Tvr65, and Tvr83) are connected together to form a polygon. The vector length and direction indicate the degree of the genotypes' response to the APV environments. A vertical line intersecting a horizontal line at the biplot origin separated the biplot into four quadrants. All variables to the left of the vertical line had below average seed yield while the variables to the right of the vertical line had above average seed yield. Likewise, all variables above the horizontal line had positive interactions whereas all variables below the horizontal line had negative interactions. Additionally, two mega-environments were created from the biplot. Mega-environment 1 had both WPV and NPV environments whereas mega-environment 2 only included the EPV. In a mega-environment, the genotype on the vertices of the polygon is considered to be the best performing genotypes in those environments for the trait under investigation (Yan and Rajcan, 2002) while genotypes that are farthest from the horizontal axis are unstable. Tvr79 was more stable within the APV environments tested since it was located close to the biplot origin and within the polygon in sector 3 although with below average seed yield whereas the other genotypes occupied the vertexes.

Tvr28 genotype had the highest yield in mega-environment 1 (WPV and NPV), while Tvr83 recorded the highest yield under EPV environment in sector 2. Genotypes Tvr65 and Tvr79 were contained in sector 3 while Tvr18 was alone in sector 4. The three genotypes, Tvr18, Tvr79, and Tvr65 recorded below average performance across the mega environments and were referred to as poor performers. Although Tvr79 was the most stable of the genotypes, its yield performance was below average, hence, Tvr28 and Tvr83 which were the next most stable genotypes were preferred having recorded above average yields. There was inconsistency in the performance of genotypes across the mega environments. The IPCA1 and IPCA2 scores of environments had both negative and positive values (Table 2) implying that there was a change in ranking order (cross-over effect) of genotypes from one environment to the other (Fig. 4).

The stability trends and crossing-over effects of the G × E interaction are illustrated in Fig. 4. The distance between the highest level of a genotype or an environment and its lowest

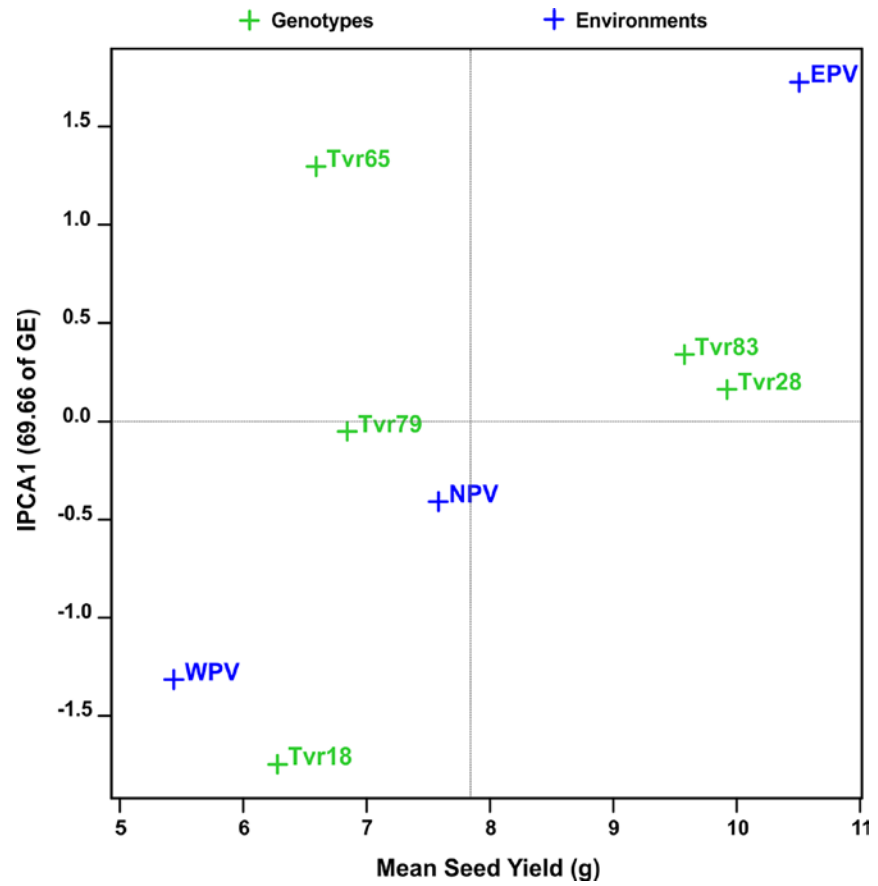

Fig. 2. Biplot of seed yield vs IPCA1 for five mungbean genotypes in three APV environments. WPV: East-West facing PV; EPV: West-East facing PV; NPV: no-PV.

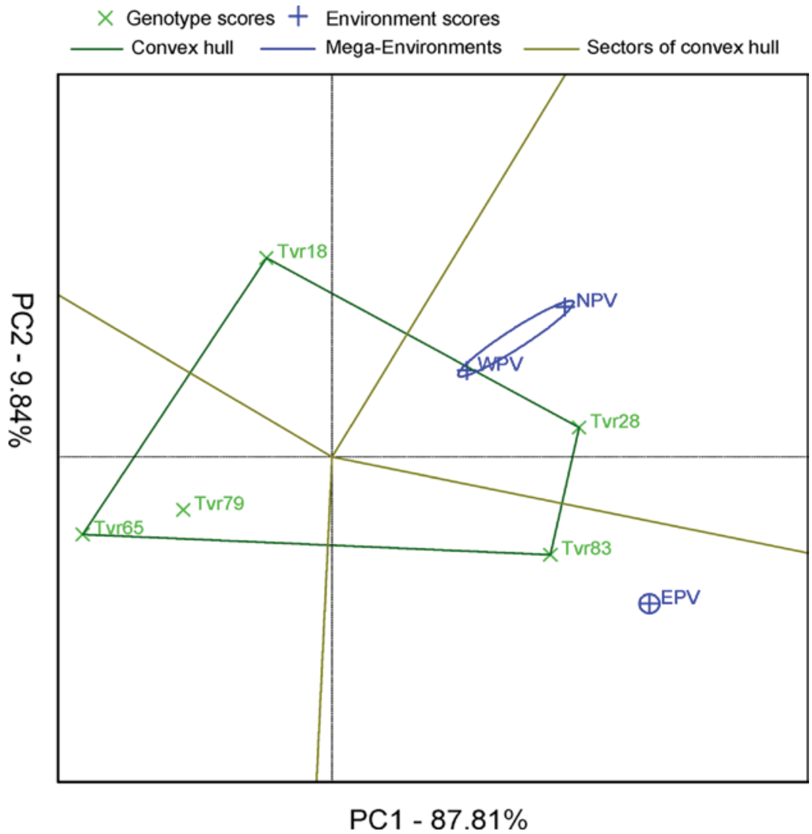

Fig. 3. GGE biplot analysis of seed yield showing which-won-where view of five mungbean genotypes in three APV environments. WPV: East-West facing PV; EPV: West-East facing PV; NPV: no-PV.

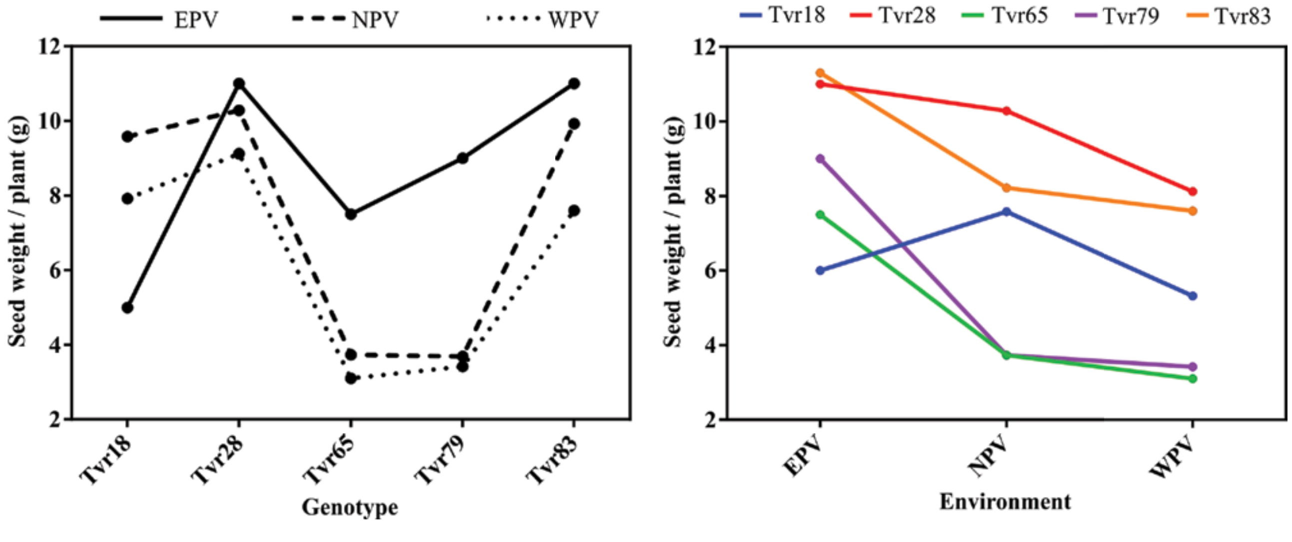

Fig. 4. Genotype by environment interaction showing stability trends and crossing-over effect. WPV: East-West facing PV; EPV: West-East facing PV; NPV: no-PV.

level indicates the stability level of that genotype or environment. The shorter the distance, the more stable the genotype. For instance, Tvr28 had the shortest distance in Fig. 4a with all three points aligning close to each other, implying that it had comparable performance across the three APV environments. Similarly, both Tvr28 and Tvr83 showed broad adaptability and recorded higher yield scores with its lines above the other genotypes (Fig.4b). Additionally, a change in ranking order of genotypes was evident. Particularly, Tvr83 ranked first in the EPV environment with the highest yield, and ranked second in both the NPV and WPV environments (Fig.4b). Also, Tvr28 ranked second in the EPV environment but ranked first in both NPV and WPV environments (Fig.4b).

The AEC method was also used to assess the yield stability of genotypes by making use of the principal components in all environments (Fig. 5). The blue line drawn through the ideal environment and the biplot origin pointed to the genotypes with the greatest effect on seed yield. The greater the distance between a genotype and the AEC coordinate, the greater the G × E interaction, and the lower the genotype stability. The AEC coordinates partitioned the genotypes with the greatest main effects (Tvr83 and Tvr28) from the genotypes with below average effects (Tvr65, Tvr79, and Tvr18). In addition, the blue line pointed to the ideal environment (EPV) that favored the full expression of the test genotypes (Fig. 6). Therefore, Tvr83 and Tvr28 with above average effect were also confirmed as the best in terms of average yield and stability, while Tvr18, Tvr65, and Tvr79 with below average effect were the poorest (Figs. 5 and 6).

The correlation among the environments is shown in the vector view of the GGE-biplot (Fig. 7). The angle between the environment vectors defines the type of relationship between any two environments. An acute angle indicates a positive correlation; an obtuse angle indicates a negative correlation while a right angle indicates no correlation. Hence, Fig. 7 showed that all the environments were negatively correlated with each other with angles greater than 90°C between them implying high environmental sensitivity of the mungbean genotypes in terms of seed yield.

Discussion

The significance of identifying the most suitable PV orientation that optimizes food production and energy generation cannot be overemphasized. The best APV environment should be able to transmit enough solar radiation for optimum photochemical energy production and electron transfer for improved seed yield (Ukwu *et al*., 2025) without negatively affecting energy generation. This study recorded significant variation in the yield of genotypes in the different APV micro-environments. The superior NOPP, NOSPt, and seed yield recorded under the EPV whole-plot in contrast to the WPV whole-plot could be implicated in the improved microclimate conditions provided by the West-east oriented PV modules which allowed sufficient PAR, improved temperature and air humidity, consequently enhancing physiological processes which manifested phenotypically as higher yield contrary to the East-west oriented type. This is in agreement with Ukwu *et al*. (2025) who reported enhanced photochemical efficiency and reduced non-photochemical energy losses of mungbean crops underneath the EPV environment compared to the WPV and NPV environments. The observed genotypic variation among the mungbean genotypes is beneficial in mungbean breeding program for maximizing genetic gain (Hallauer and Miranda, 1988). This report is consistent with widely reported genotypic variation in mungbean (Gayacharan *et al*., 2020; Mwangi *et al*., 2021; Yoseph *et al*., 2022; Ukwu *et al*., 2023b, 2024).

The variation explained by genotype (27%) was the highest after environment indicating some level of diversity among the selected genotypes used for the study. Due to the differential responses of genotypes across the APV micro-environments, the conventional analysis of variance was unsuitable to capture the extent of G × E interaction. Hence, this study adopted both the AMMI and the GGE biplot analyses simultaneously in order to correctly estimate the G × E interaction effect. The AMMI ANOVA showed that the G × E interaction sum of squares (170.5) was comparable in size to that of the genotype sum of squares (185.0), implying that the response of some genotypes was similar in at least one environment. The AMMI ANOVA further partitioned the significant G × E interaction variance into IPCA1 and IPCA2, which explained 70 and 30% of the interaction variance, respectively (Table 3). This report is coherent with findings by Mattos *et al*. (2013), Regis *et al*. (2018), and Tena *et al*. (2019), who reported that the greater percentage of the G × E interaction effect was accounted for by IPCA1.

The ability of a genotype to produce a high yield in an environment and maintain its high-yielding ability when grown in new environments or across years is a very important aspect of crop improvement. Plant breeders are interested in genotypes that could consistently maintain its high yielding ability over time and across locations with minimal fluctuations. A genotype is described as stable if its mean yield is high with minimal variation in yielding ability when

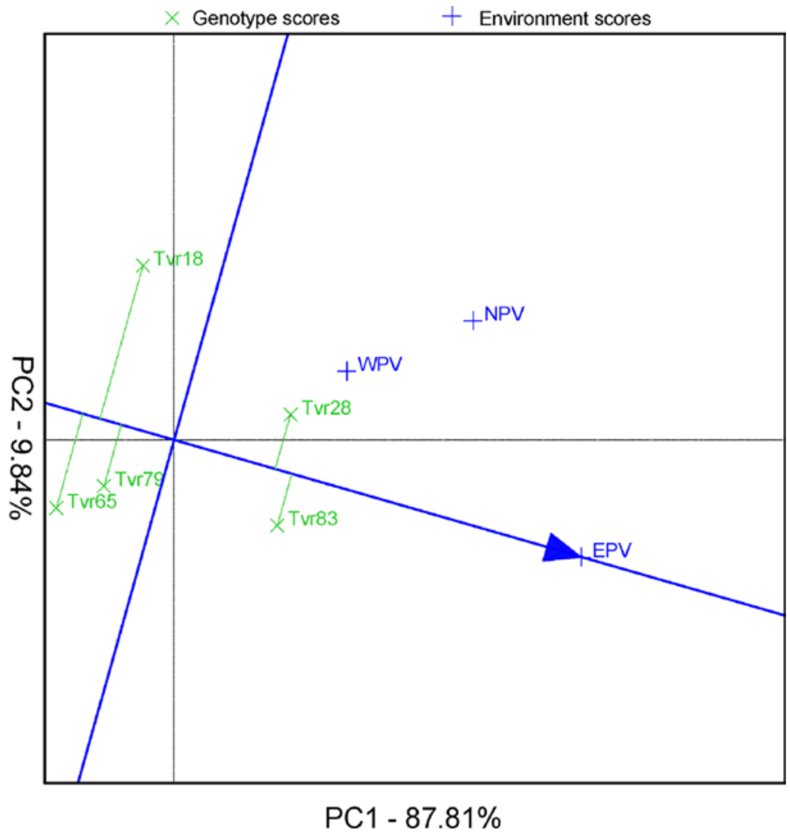

Fig. 5. Average environment coordination (AEC) view of the GGE-biplot based on environment focused scaling for the means performance and stability of genotypes. WPV: East-West facing PV; EPV: West-East facing PV; NPV: no-PV.

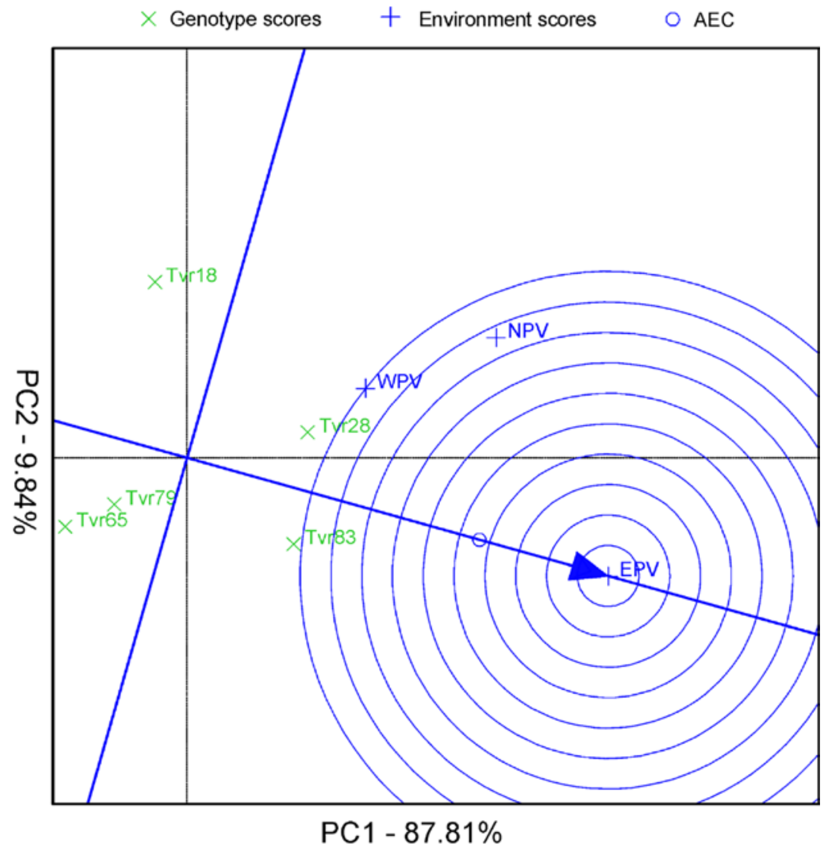

Fig. 6. Comparison GGE-biplot discriminating the genotypes with the above average yield from the genotypes with below average yield across the APV environments. WPV: East-West facing PV; EPV: West-East facing PV; NPV: no-PV.

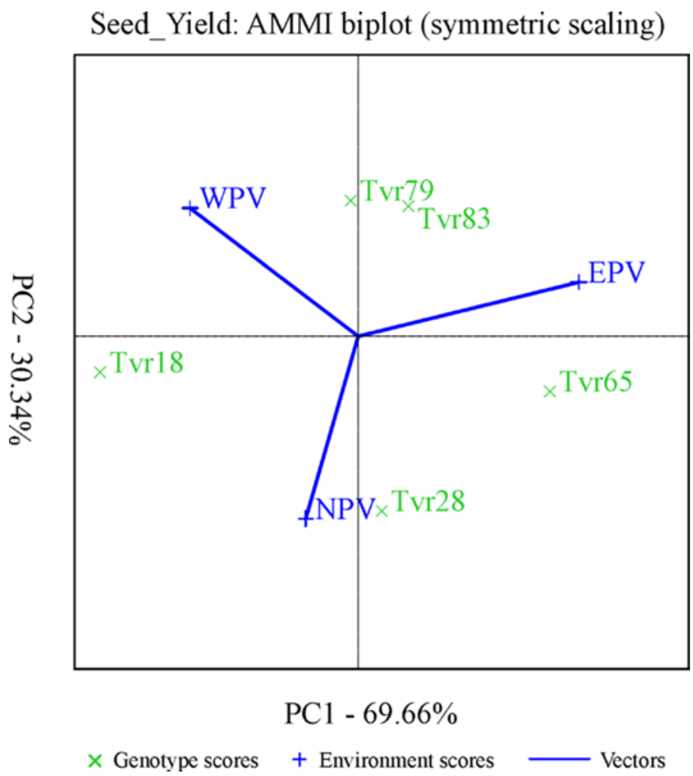

Fig. 7. GGE-biplot based on environment-focused scaling for environments. WPV: East-West facing PV; EPV: West-East facing PV; NPV: no-PV.

assessed across different environments (Yadesa, 2022). The AMMI stability index (ASV) is widely recognized as an effective method for assessing genotype stability and has been widely used alongside other stability metrics like Eberhart and Russel, Shukla, and Wrick (Purchase *et al*., 2000). The study showed that Tvr83 and Tvr28 had the least ASV coefficients and were the more stable genotypes across the APV micro-environments in contrast to Tvr18 and Tvr65 which were the most unstable genotypes. The significant G × E interaction for mungbean yield indicates that both genotype and environment influenced yield variation, with neither factor alone explaining it. G × E interaction affects the outcome of any selection process and is an important component of any plant breeding program (Bhagwat *et al*., 2018). The variable responses of genotypes across the APV micro-environments highlight the importance of selecting stable and well-adapted genotypes for APV systems. Although, a low G × E interaction effect is desired by a plant breeder for stability across multi-environments, a high G × E interaction can be advantageous when breeding for a specific environment (Nath and Dasgupta, 2013).

Despite the higher sensitivity of the NPV and WPV environments, seed yield was still below average (<7.8 g) and were considered not ideal. In contrast, the environment EPV which showed less discriminatory effect on mungbean genotypes influenced superior mungbean yield (10.5 g). Remarkably, the EPV environment also favoured the genotypes Tvr28 and Tvr83 which were the best in terms of yield.

There was inconsistency in the performance of at least one genotype across the mega environments. The environment IPCA1 and IPCA2 scores had both negative and positive values (Table 2) implying that there was a difference in ranking orders among genotypic yield performances across environments (Fig.4). Rank order change represents the highest level of G × E interaction effect. The implications of a rank order change are enormous. It indicates an inconsistency in the performance of a genotype across diverse environments as typified by Tvr18, Tvr28 and Tvr83 (Fig. 4a), which further emphasizes the importance of considering G × E interactions in any crop improvement programs to ensure that new varieties are adapted to a range of environments. This could increase their potential for widespread adoption. These findings corroborate Regis *et al*. (2018) and Tena *et al*. (2019). Furthermore, the GGE comparison biplot (Fig. 5) was also used to screen the ideal genotype. An ideal genotype is the genotype with the highest mean performance and is stable (Yan and Kang, 2003). It should have a high mean yield across all environments. It is graphically identified by the longest vector in PC1 and without projections in PC2. Therefore, the genotypes Tvr83 and Tvr28 were the closest to the ideal genotypes. The angles between the environments show their inter-relationship with one another. The three APV micro-environments were negatively correlated with each other having angles greater than 90°C between them (Fig. 6) implying high environmental sensitivity of the mungbean genotypes in terms of seed yield. Hence, a genotype that excelled in the EPV environment is unlikely to exhibit similar performance in either of WPV or NPV environments. Although most researchers have reported positive correlations between test environments, negative correlations have also been reported by Mattos *et al*. (2013) and Tena *et al*. (2019).

The differential responses of the mungbean genotypes to the contrasting APV environment are a consequence of the differences in their genetic constitution and preference for shade or reduced light conditions which had previously been reported by Ukwu *et al*. (2023b, 2024, 2025) and consistent with Banik *et al*. (2010). The large environmental variation could be implicated on the effect of the PV modules in moderating the microclimate condition of the APV environments (Fig. 1). Microclimate indices of a plant such as PAR, temperature, and relative humidity exert considerable influence on crop growth and development. Crops perform optimally under specific climatic conditions, and any sharp deviation from the optimal could greatly affect crop productivity (Ukwu *et al*., 2025). PAR and temperature were decreased under the WPV and EPV environments compared to the control (No PV shading) environment due to the effect of the PV-modules in shading-off some proportion of incident radiation consequently exerting a cooling effect with reduced evapotranspiration. The variation in the performance of the APV environments, specifically between the WPV and EPV, could have arisen from the direction of the PV panels. Although the same PV panels were used, PV direction was different which emphasizes the significance of panel orientation when installing an APV facility. This study recorded higher PAR and temperature values with lower relative humidity under the EPV compared to the WPV which could be implicated on the rising of the sun from the East and setting at the West implying that the EPV had more sun hours compared to the WPV which significantly affected mungbean yield. The change in the ranking order of genotypes illustrated by crossing-over interactions in Fig. 4, is a confirmation of a strong G × E interaction among mungbean genotypes. This occurrence could greatly affect mungbean breeding programs. A strong G × E could reduce the heritable variance, selection efficiency, and predictability of a genotype (Falconer, 1952) which underscores the significance of selecting broadly adapted genotypes for mungbean improvement studies in order to guarantee a high success rate. The objective of this study was to select genotypes with superior yield advantage and greater stability underneath the APV system. Hence, the genotypes Tvr28 and Tvr83 having recorded the highest yields with greater stability index were the best. These genotypes are therefore recommended for varietal development program on the premise of their superiority in yield in the EPV environment and adaptability across contrasting APV environments which is in agreement with Lal *et al*. (2018).

CONCLUSIONS

The study aimed to investigate the yield performance of mungbean genotypes under contrasting APV micro-environments to select high-yielding and stable genotypes for APV systems in the tropics. Environment, genotype, and G × E interaction effects significantly affected mungbean yield. The environment accounted for the largest proportion of the observed variation and was followed by genotype and G × E interaction, respectively. Two genotypes Tvr28 and Tvr83 were the best in yield and stability. The EPV environment had the highest yield and was favorable to the two best yielding genotypes. The AMMI analysis was able to partition the G × E interaction into IPCA1 and IPCA2 accounting for 70 and 30%, respectively. The IPCA1 and the GGE biplot analyses confirmed that Tvr28 and Tvr83 were the best performers while the EPV environment was the closest to an ideal environment with the highest seed yield across the APV environments and is therefore recommended for screening genotypes for use in an APV facility. The percentage of explanation of the sum of squares was high by both the AMMI and GGE-biplot methods. This study is the first to demonstrate the adaptability of mungbean genotypes to different APV orientations. Hence, more research is needed to identify adaptable genotypes for different crops underneath an APV facility for sustainability.

ABBREVIATIONS

AMMI	Additive main effects and multiplicative interaction
APV	Agrophotovoltaics
EPV	West east facing photovoltaic panels
GGE	Genotype by genotype by environment
PV	photovoltaic panels
NOPP	Number of pods per plant
NOSPd	Number of seeds per pod
NOSPt	Number of seeds per plant
NPV	No photovoltaic panels

NS	No significant difference
WPV	East west facing photovoltaic panels
SW	Seed weight

CONFLICTS OF INTEREST

The authors have declared that they have no competing interest.

ETHICS STATEMENT

The authors confirm that the research meets any required ethical guidelines, including adherence to the legal requirements of the study country.

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AUTHOR CONTRIBUTIONS

UNU, OM, MM and MIU contributed to the study conception, design, material preparation, and review. Data collection and analysis was performed by UNU. The first draft of the manuscript was written by UNU. All authors commented on the previous versions of the manuscript, read and approved the final manuscript.

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DATA AVAILABILITY

All data generated or analyzed during this study will be available on request from the corresponding author.

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